Determination of Neutron Irradiation damage to COPS CCDs. (PRELIMINARY)

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1. Introduction

The EMU alignment system must withstand the hostile environment in CMS. The biggest threat from this environment arises from the radiation damage on the alignment elements caused by the accumulated neutron fluence throughout years of CMS running.

Calculations on the expected neutron fluence, after 10 CMS years, have been performed by Huhtinen [sp] and accepted as official CMS parameters. Table 1 shows the neutron fluence, multiplied by a safety factor of 3, at the different locations of the alignment sensors. The highest fluence is expected at the innermost radial position in station ME2/1, where it will be 3 x 10^{12} n/cm2.

Table 1

Neutron Radiation Dose in 10 Years at CMS **(x3 safety factor included)**

Station	Z(mm)	R1(mm)	dose in neutrons/cm^2	R2(mm)	dose in neutrons/cm^2	Max Dose in Station
ME1/2	6665	2825	**5.9 x 10^{10}**	4605	**3.2 x 10^{10}**	
ME1/3	6840	5100	**9.8 x 10^{9}**	6800	**1.5 x 10^{10}**	**6 x 10^{10}**
ME2/1	7876	1500	**3.2 x 10^{12}**	3400	**3.7 x 10^{10}**	
ME2/2	7876	3700	**2.8 x 10^{10}**	6800	**2.6 x 10^{10}**	**3.2 x 10^{12}**
ME3/1	9714	1700	**7.5 x 10^{11}**	3400	**1.3 x 10^{11}**	
ME3/2	9714	3700	**9.4 x 10^{10}**	6800	**4.1 x 10^{10}**	**7.5 x 10^{11}**
ME4/1	10620	1900	**7.4 x 10^{11}**	3400	**1.5 x 10^{11}**	
ME4/2	10620	3700	**1.3 x 10^{11}**	6800	**8.3 x 10^{10}**	**7.4 x 10^{11}**

At theTransfer plates (R=7250), dose ranges between **3 x 10^{10}** and **8 x 10^{10}**

(From K. Maeshima's E-mail 9/23/99, based on numbers supplied by M. Huhtinen)

We report here on the measurement of the radiation damage effects in linear CCD sensors, and in laser modules.

2. The test samples.

COPS are the main sensors in the EMU alignment system. As described elsewhere [for instance, D. Eartly et al., CMS Note/96-021, and J. Moromisato et al. NIM A426(1999)375], they are based on an arrangement of four linear CCDs illuminated by cross-hair laser beams. The CCDs were considered susceptible to radiation damage, thus it was particularly important to ascertain that they could operate satisfactorily in CMS.

The laser modules and the readout electronics for the CCDs, could also be vulnerable to neutron radiation. However both of them are located in regions where the neutron fluence is about one order of magnitude below the hottest position for the CCDs. Nevertheless, two laser modules were exposed to their expected neutron fluence, 8×10^{10} n/cm2 (which include the safety factor of 3).

Twelve CCD ICs, of the type used in the COPS were exposed to neutrons at a radiation facility. Prior to that, most of them were tested in a dark box where their responses to an LED were recorded. However the CCDs were very similar in their responses so there was no need to use the dark box results.

The CCDs were set on a sheet of paper with millimetric grid, at selected locations. The paper was attached to a cardboard piece, for rigidity. The expected fluence at the selected locations were determined using a fluence map provided by the radiation lab.

3. The radiation facility.

The irradiation was carried out at the Radiation Laboratory of the University of Massachusetts Lowell. The neutron field was generated by a 4 MeV proton beam, from a van-de-Graaff accelerator, absorbed by a ^{7}Li target [Ref: G. Kegel and D. DeSimone, NIM A426(1999)61]. With a 17mm target diameter, the isofluence lines are almost concentric circles, with a fluence of 1.3×10^{13} n/cm2 per hour at a distance of 18mm from the target center, and a ten times lower fluence at a distance of 60mm. This large range of neutron fluences available from one single source allows testing at different radiation dose in one single exposure session. On the other hand, the large point to point variation in the fluence imposes some constraints on the size of the test sample. In our case, the test samples were small enough so that the neutron field inhomogeneity was not much of a problem.

The determination of the actual neutron fluence, at any given point in the neutron field, was done by the radiation lab staff, by measuring the activation of the Lithium target, after the irradiation period. An alternate determination, done using the integrated proton current, was consistent with the activation results.

The neutron fluence was adequate for our purposes, and it took an 8-hour irradiation to complete the exposure. The maximum total fluence received by the CCD with the highest exposure was 1.2×10^{13} n/cm2. A group of 5 CCDs, out of the 12 that were irradiated, had only a 1-hour exposure, but were located closer to the target.

Table 2

Radiation Test 10/7/99 Data

J. Moromisato 10/6/99

IC #	Position #	Row	Column	Exp. Time	Fluence	Comment
A1	1	17	5.5	8hrs	**1.2×10^{13}**	
A2	2	17	7.5	"	**6.2×10^{12}**	
A3	3	21	9	"	**3.2×10^{12}**	
A4	4	25	10	"	**1.6×10^{12}**	
B1	15	14	2	**1hr**	**1.9×10^{12}**	
B2	16	13	6	**"**	**6.6×10^{11}**	
B3	17	12	10	**"**	**2.9×10^{11}**	
B4	18	6	11	**"**	**1.2×10^{11}**	
C1	19	2	8	**"**	**7.5×10^{10}**	
C3	31	2	12	8hrs	**5.8×10^{11}**	with lucite prism
D1	32	24	5	"	**2.8×10^{12}**	"
D2	33	27	7	"	**1.3×10^{12}**	"
laser 001	44	4	2	**1 hr**	**8.5×10^{10}**	
laser 002	45	4	12	**"**	**8.5×10^{10}**	

NOTE: Row and column numbers refer to 'Neutron Fluence Map' (Umass Lowell Radiation Lab)

Table 2 shows the total neutron fluence received by the CCDs and laser modules used in the test.

4. The CCDs Evaluation.

The irradiated CCDs were tested at the Northeastern optical lab, and their response in terms of dark current level, pixel response uniformity, and laser peak determination, were correlated with the neutron fluences to which they were exposed.

The initial tests after irradiation were done using an old COPS prototype, because the new prototypes were not available then. The dark current spectra of the irradiated CCDs, are shown in Fig.1. The plots show that the dark current spectra saturate the COPS readout even at neutron fluence levels around 7×10^{11} n/cm^2. We understood early on that the COPS response was determined by the

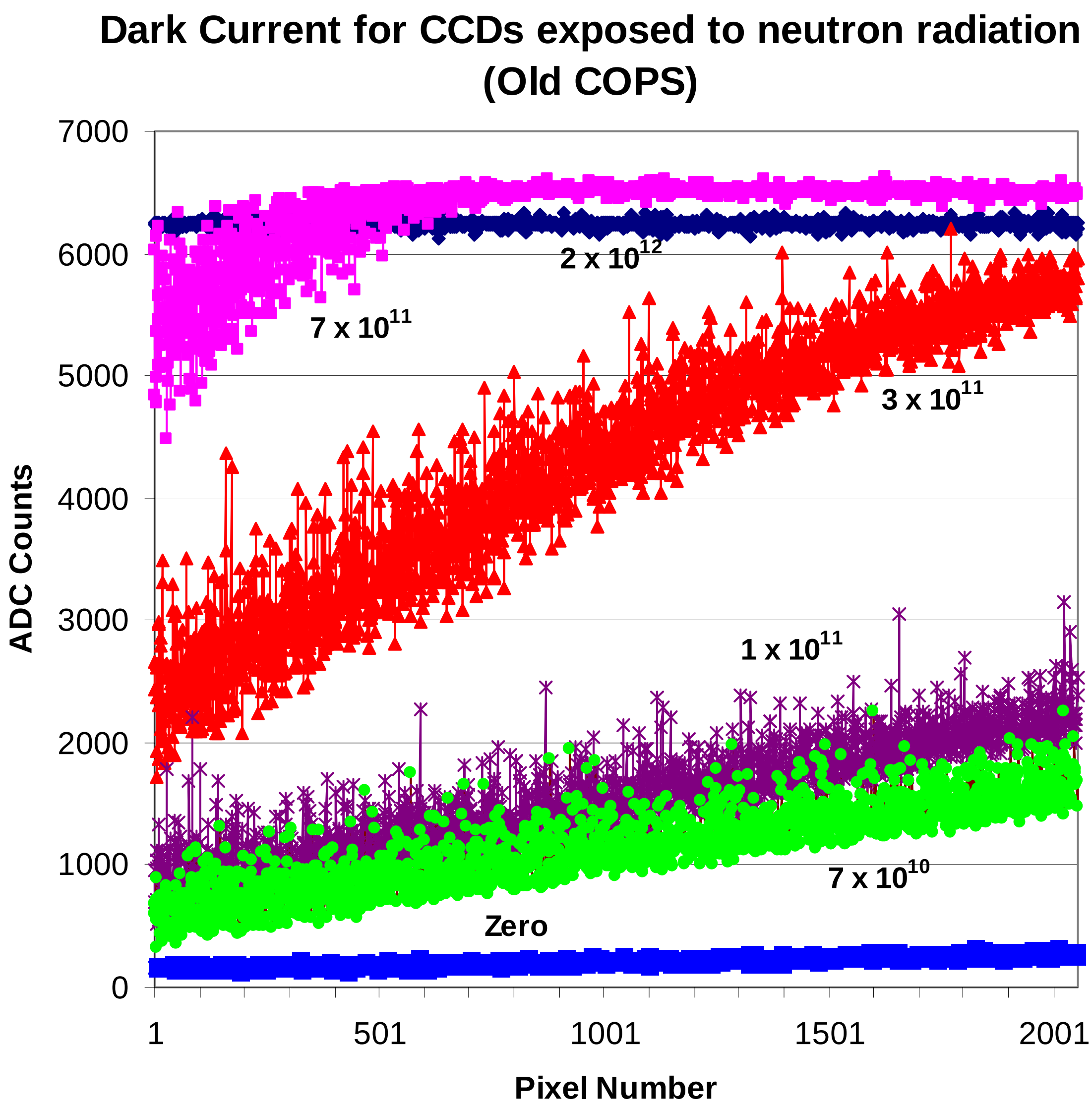

Fig 1. Dark current spectra for irradiated CCDs, taken with the old COPS prototype. The readout was very slow, thus magnifying the effect of the

readout speed, as will be described below, and that the results would be very different with the new COPS prototype.

We have now the results of measurements taken with the new version of COPS. They show that the CCDs are still operational, namely the dark current is far from saturating the ADC, after being exposed to the fluence level expected in 10 years of running at CMS (safety factor of 3 included). The new COPS prototype was designed and produced before the radiation tests were performed, thus they have not been optimized for speed. A brief description of how the CCDs work is now in order.

The Sony ILX503A CCD, used in COPS, consists of a linear array of 2048 photodiodes or pixels, each 14 x 14 micron squared. The photodiodes are connected to an equal number of shift registers, through a common switch. The photodiodes will continuously convert the incoming photons into electric charges, which are transferred to the shift registers as soon as the common switch opens. The shift registers are then readout into an ADC chip to digitize the CCD response. The charge collected in each CCD pixel is proportional to the incoming light intensity and to the exposure time. The exposure time is simply the time between two consecutive openings of the common switch. The dark current in the CCD, basically a leakage current, occurs during the exposure period and also during the shifting or readout period. The characteristics of the dark current spectrum depend on the relative duration of these two periods: the exposure and the shifting periods.

The exposure period determines the height of the curve, at the lowest pixel (left hand side of the plot), while the shift period determines the slope of the curve. The plots in Fig.1 were taken in the dark and show very clearly these two features of the dark current. The slopes, in particular, are very noticeable, and contribute to the saturation of the irradiated CCDs.

Both, the exposure and the shifting periods can be separately set, although they could not be changed in the old COPS. We knew that those periods were much larger than necessary, and that they would be substantially reduced in the new COPS.

The latest COPS prototype boards became available soon after the initial tests were made.

Fig 2, shows the dark current spectra for the same CCDs in Fig 1, but taken with the new COPS prototype. As before there is a clear correlation, as expected, between the neutron fluence received, and the height of the dark current spectrum. The highest dark current level, in Fig 2, corresponds to

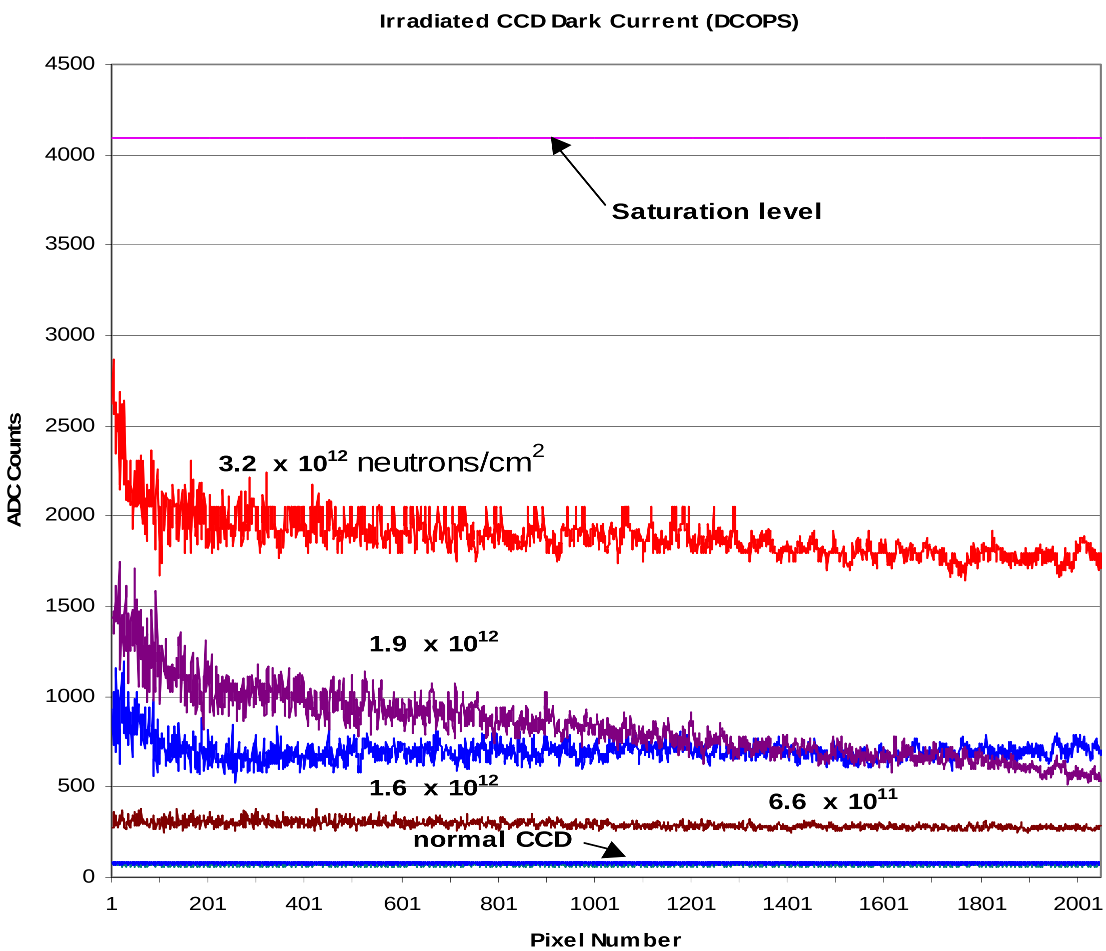

Fig 2. Dark current spectra for the irradiated CCDs. The numbers next to the plots correspond to the radiation dose, in neutrons/cm2. The horizontal line at the bottom correspond to a non-irradiated CCD. The rise at low pixel numbers, in the three top plots, are not well understood but, since the background substraction will eliminate any trace of it, it was not investigated further.

CCD D1. The curves showing almost negligible background correspond to normal, non-irradiated CCDs.

As expected, the new COPS board has a faster shift register readout, as demonstrated by the almost imperceptible slope of the dark current spectra, and also a shorter exposure time, which explain the reduced level of dark current in all the CCDs shown.

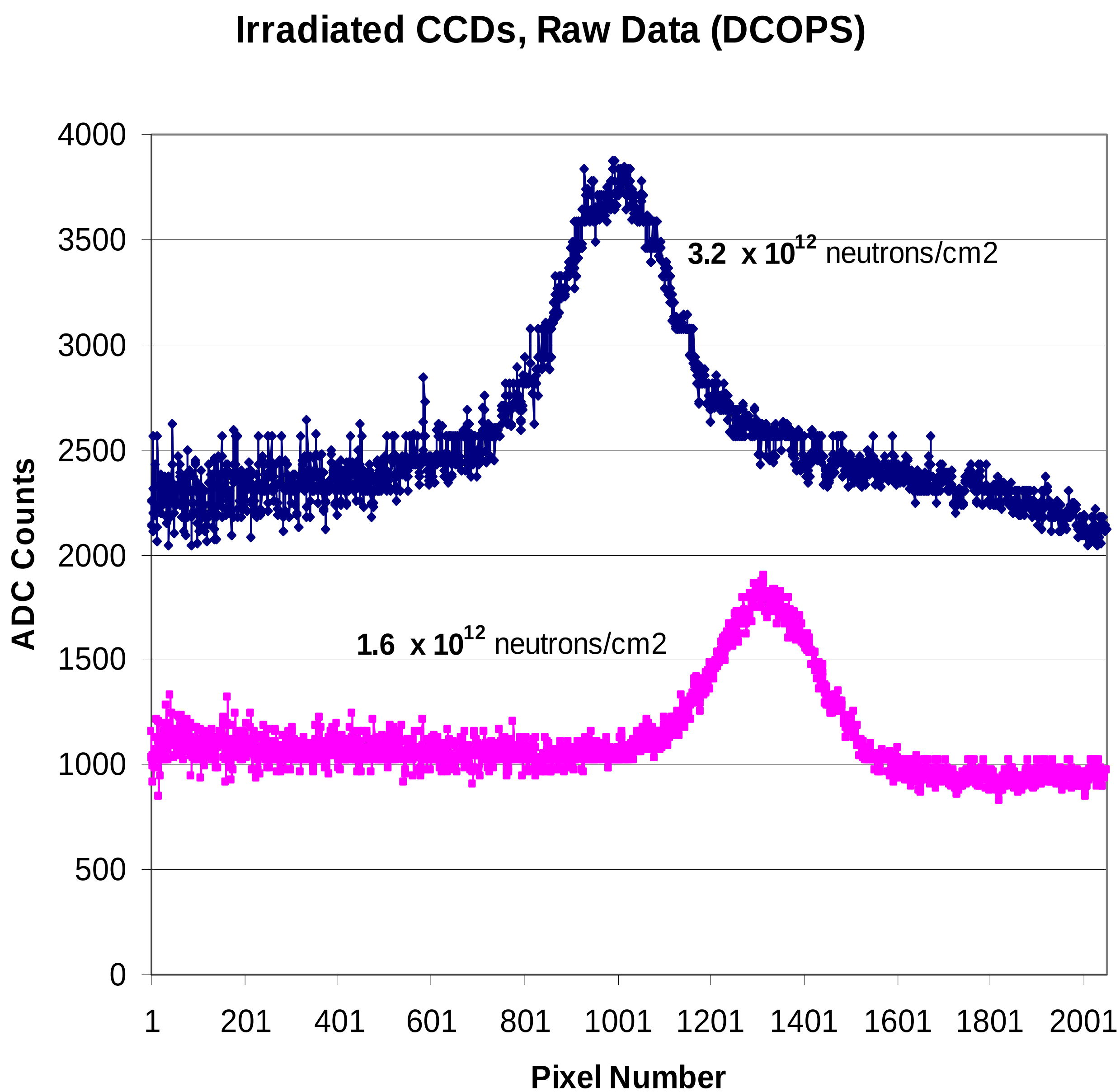

Fig 3. Raw spectra of two of the irradiated CCDs, showing the peaks produced by the laser lines.

In addition to increasing the dark current level, neutron irradiation affects the CCDs by increasing the pixel to pixel sensitivity, although the CCD response to the cross-hair laser looks otherwise normal, as shown in Fig 3. The plot with the higher overall ADC level corresponds to CCD D1.

To test for any possible effect from radiation damage to the linearity of the CCDs, we tested again the CCD D1. Fig 4 shows that any radiation damage effect on the CCD's pixel sensitivity is too small to be seen in the linearity check.

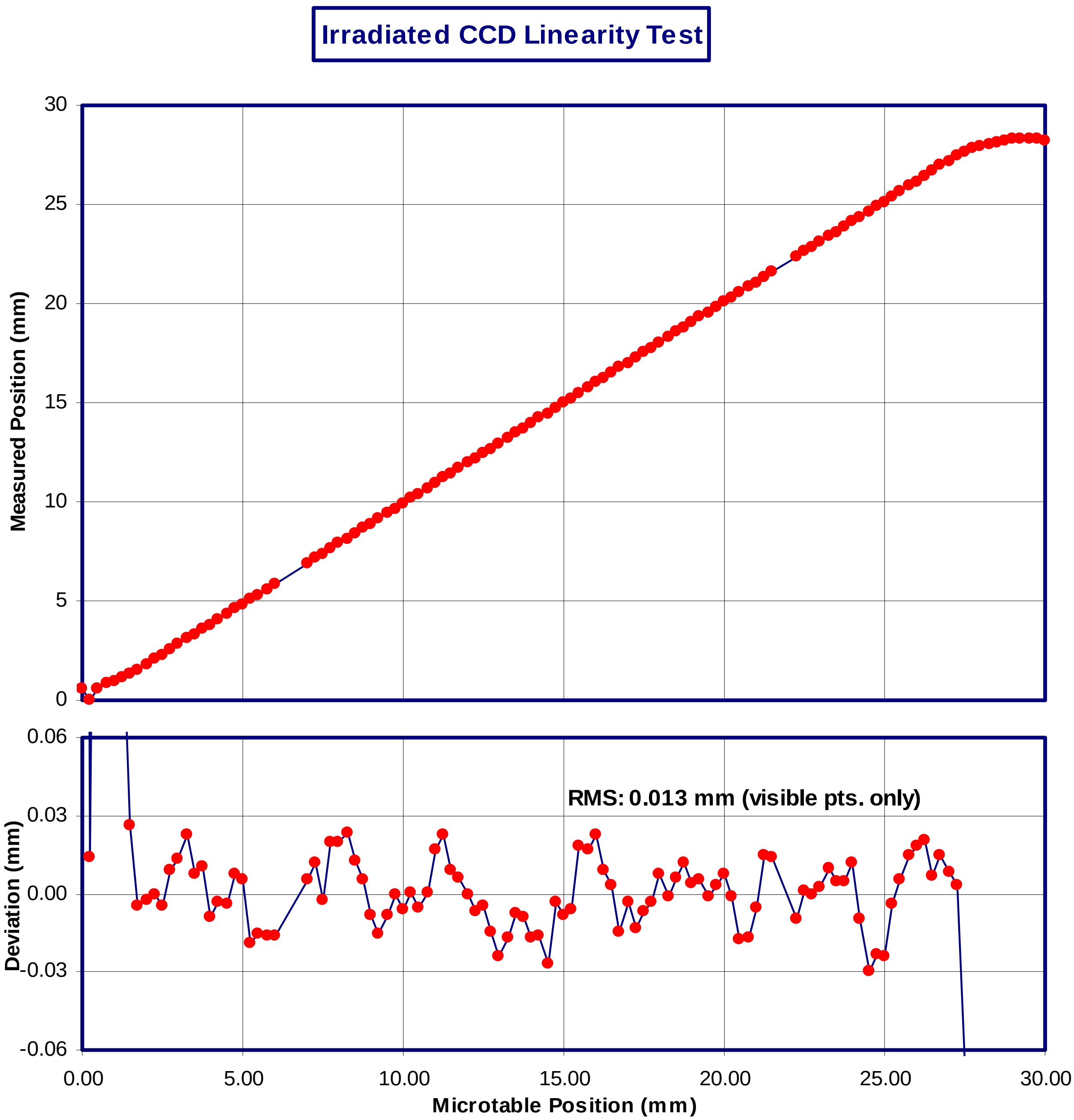

Fig. 4. Linearity test on CCD D1, which was exposed to a neutron dose equal to the 3 times the expected fluence in a 10-year CMS run. Notice that the linear range extend for more than 25mm.

5. Summary and Conclusions.

The expected integrated neutron fluence, for a 10-year CMS run, varies for the different alignment sensors positions from 6 x 10^{11} neutrons/cm2 at ME1/2,3, to 3 x 10^{12} n/cm2 (including the safety factor of 3) at the innermost position in ME2/1 . In order to test the radiation hardness of the COPS, we have exposed a dozen linear CCD ICs (Sony ILX503A) to various levels of neutron fluences at the UMASS Radiation Laboratory at Lowell, MA. Measurements on the exposed ICs yield the following conclusions:

1. Effects of the neutron irradiation are noticeable even below 1 x 10^{11} n/cm2.
2. The effects manifest themselves in two ways:
   i) through an increase in the dark current, or background level, and
   ii) In the higher fluctuation in relative pixel to pixel sensitivity.

1. The dark current in the CCDs, caused by charge leakage during exposure to laser light and shifting time, increases by over one order of magnitude after a dose of 3.2 x 10^{12} n/cm2. As mentioned above, the dark current level depends linearly on the speed of the readout process, and that in turn depends on the hardware characteristics of the readout board. Faster ADCs, and faster shift rates can substantially lower the background. However, the results obtained with the current version of COPS are perfectly satisfactory, thus any improvement is the readout speed will be desirable but not really necessary.
2. A linearity check performed on one of the CCDs with highest radiation dose (3.2 x 10^{12} n/cm2) shows (Fig 4) that the deviation from linearity is around 13 microns, and fully consistent with previous linearity measurements on non-irradiated CCDs. In other words, the neutron irradiation had, if any, a very small effect on the response linearity of the CCDs.
3. The increased fluctuation in pixel to pixel sensitivity may in turn affect the precision of the peak position determination. For our application, any such degradation in position resolution has a negligible contribution to the overall alignment error (required to be about 100 microns).
4. Finally, we conclude that the CCDs at the heart of the COPS sensors will withstand the total neutron fluence expected in a 10-year CMS run (including the x 3 safety factor).